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# Solving the Gravitino Problem by Axino

T. Asaka[1] and T. Yanagida[1,2]

[1] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*

[2] *Research Center of the Early Universe, University of Tokyo, Tokyo 113-0033, Japan*

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## Abstract

In a large class of supersymmetric (SUSY) axion model the mass of axino $\widetilde{a}$ (a fermionic superpartner of the axion) is predicted as $m_{\widetilde{a}} \lesssim \mathcal{O}(1)$ keV. Thus, the axino is the lightest SUSY particle (LSP). We pointed out that such a light axino provides a natural solution to the gravitino problem, if the gravitino is the next LSP. We derive a constraint on the reheating temperature $T_R$ of inflation, $T_R \lesssim 10^{15}$ GeV for the gravitino mass $m_{3/2} \simeq 100$ GeV, which is much weaker than that obtained in the minimal SUSY standard model.

The CP violation in QCD is one of the most serious problems in the standard model. In spite of continuous effort to solve the strong CP problem in the last coupled decades, the mechanism proposed by Peccei and Quinn [1] is still the most attractive one. The spontaneous breakdown of the Peccei-Quinn symmetry produces a Nambu-Goldstone boson (called as axion "$a$") [2] and the breaking scale $F_a$ is stringently constrained by laboratory experiments, astrophysics and cosmology as $F_a \simeq 10^{10}$–$10^{12}$ GeV [3].

Supersymmetric (SUSY) extension of the Peccei-Quinn mechanism necessarily predicts a fermionic partner of axion,[1]so-called axino $\widetilde{a}$, whose mass is highly dependent of models [4–6]. However, in a large class of SUSY axion models [6] the mass of axino is predicted in the region $m_{\widetilde{a}} \lesssim \mathcal{O}(1)$ keV which is cosmological harmless [5]. In these models the axino $\widetilde{a}$ is the lightest SUSY particle (LSP) and the gravitino $\psi_{3/2}$ can decay into a pair of the axion $a$ and the axino $\widetilde{a}$. We point out, in this letter, that the light axino provides a natural solution to the cosmological gravitino problem [7], if the gravitino $\psi_{3/2}$ is the next LSP. We assume that the axino $\widetilde{a}$ is the LSP of mass $m_{\widetilde{a}} \lesssim \mathcal{O}(1)$ keV and the gravitino is the next LSP of mass $m_{3/2} \simeq 10^2$ GeV throughout this letter.[2]

Then, the main decay of the gravitino $\psi_{3/2}$ is $\psi_{3/2} \rightarrow \widetilde{a} + a$ and its lifetime is estimated as

$$\tau_{3/2} \sim 10^9 \ \text{sec} \ \left(\frac{10^2 \ \text{GeV}}{m_{3/2}}\right)^3 . \tag{1}$$

Since $\widetilde{a}$ and $a$ have very weak couplings to the ordinary particles, this gravitino decay does not destroy any light nuclei synthesized at the epoch of big-bang nucleosynthesis (BBN). The ratio of the gravitino energy density to the entropy density is given by [7]

$$\frac{\rho_{3/2}}{s} \sim 10^{-9} \ \text{GeV} \ \left(\frac{m_{\widetilde{g}}}{1 \ \text{TeV}}\right)^2 \left(\frac{T_R}{10^{10} \ \text{GeV}}\right) \left(\frac{m_{3/2}}{10^2 \ \text{GeV}}\right)^{-1} , \tag{2}$$

where $m_{\widetilde{g}}$ is the gluino mass. The ratio $\rho_{3/2}/s$ in Eq. (2) should be smaller than about $10^{-4}$ GeV. Otherwise, this extra energy density raises the expansion rate of the universe at the BBN epoch and leads to overproduction of $^4$He. This gives an upper bound on the reheating temperature as $T_R \lesssim 10^{15}$ GeV for $m_{3/2} = 10^2$ GeV.[3]

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[1]The axion supermultiplet $\Phi$ can be written by $\Phi = \sigma + ia + \sqrt{2}\theta\widetilde{a} + \theta^2 F_\Phi$, where $a$ denotes an axion, $\sigma$ a saxion, and $\widetilde{a}$ an axino.

[2]This possibility was considered in the context of the galaxy formation [8]. However, the gravitino is assumed to have a much longer lifetime than the estimate in Eq. (1), and hence their analysis in not applicable for the present purpose. Furthermore, cosmological constraints on the SUSY axion model discussed in this letter were not investigated there.

[3]A similar constraint on $T_R$ was obtained for the lighter gravitino of mass $\sim 100$ MeV in Ref. [8] from their scenario of the structure formation. However, our condition from Eq. (2) leads to a more stringent constraint on the reheating temperature $T_R \lesssim 10^{12}$ GeV for such a light gravitino.

On the other hand, the lightest SUSY particle $\widetilde{\chi}_L$ next to the gravitino decays into a gravitino emitting photons. If this is only the decay mode, the energetic photons destroy the light nuclei and cause a serious problem in the BBN [7]. This is because the decay takes place soon after the BBN ends. However, in the present model such a particle can decay mainly into an axino and a photon,[4]and its decay lifetime is [9][5]

$$\tau_{\widetilde{\chi}_1} \sim 10^{-3} \ \text{sec} \ \left(\frac{F_a}{10^{11}\ \text{GeV}}\right)^2 \left(\frac{10^2\ \text{GeV}}{m_{\widetilde{\chi}_1}}\right)^3 . \tag{3}$$

That is, it decays much before the BBN starts and hence there is no problem at all.

Thus, the problem we must discuss below is whether the SUSY axion model with the light axino is cosmologically safe or not. First, we discuss cosmological abundance of $\widetilde{a}$, especially, the overclosure problem of the LSP axino.

Let us discuss possible production mechanisms of the axinos $\widetilde{a}$. In the early universe the axinos are produced in the thermal equilibrium though the reactions like $q\overline{q} \leftrightarrow \widetilde{a}\widetilde{g}$, and it decouples from the thermal bath at the cosmic temperature [5]

$$T_d \sim 10^9\ \text{GeV} \left(\frac{F_a}{10^{11}\ \text{GeV}}\right)^2 . \tag{4}$$

If the reheating temperature of inflation is higher than this decoupling temperature ($T_R \gg T_d$), the yield of the axino $Y_{\widetilde{a}}$ ($Y_{\widetilde{a}} \equiv n_{\widetilde{a}}/s$ with the axino number density $n_{\widetilde{a}}$ and the entropy density $s$) is estimated as

$$Y_{\widetilde{a}} \equiv \frac{n_{\widetilde{a}}}{s} \sim 10^{-3} . \tag{5}$$

On the other hand, for $T_R \ll T_d$, the yield of the axino is given by

$$Y_{\widetilde{a}} \sim 10^{-3} \left(\frac{T_R}{T_d}\right) . \tag{6}$$

For the case of the stable LSP axino, the present energy density of the axino may exceed the critical density of the present universe in some parameter regions. The density parameter of the axino is

$$\Omega_{\widetilde{a}} = \frac{m_{\widetilde{a}} Y_{\widetilde{a}}}{\rho_c/s_0} , \tag{7}$$

where $\rho_c$ is the critical density and $s_0$ denotes the total entropy density of the present universe ($\rho_c/s_0 = 3.6 \times 10^{-9} h^2$ GeV with the Hubble parameter $h$ in unit of 100 km/sec/Mpc.). From Eq. (5) we find

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[4] $\widetilde{\chi}_L$ is assumed to be mainly composed of the photino $\widetilde{\gamma}$.

[5] If the $R$-parity is broken, $\widetilde{\chi}_L$ can decay into the ordinary light particles avoiding the problem in the BBN.

$$\Omega_{\tilde{a}} h^2 \simeq 5.8 \times 10^5 \left( \frac{m_{\tilde{a}}}{1 \text{ GeV}} \right) . \tag{8}$$

Therefore, the non-overclosure limit $\Omega_{\tilde{a}} h^2 \lesssim 1$ gives the upper bound on the axino mass as [5]

$$m_{\tilde{a}} \lesssim 2 \text{ keV} . \tag{9}$$

On the other hand, if $T_R < T_d$, we find that the upper bound (9) is relaxed as

$$m_{\tilde{a}} \lesssim 2 \text{ keV} \left( \frac{T_d}{T_R} \right) . \tag{10}$$

It should be noted here that we have a large class of SUSY axion models [6] with such a light axino, as mentioned in the introduction.

The axinos are also produced by the decays of gravitino and $\tilde{\chi}_L$. However, they are safely neglected because the axino mass should be small enough to satisfy the condition Eq. (9) or (10).

Next, we turn to discuss the cosmological problem associated with the saxion $\sigma$. The saxions are also produced through the thermal scattering processes as well as the axinos, and its decoupling temperature is also given by Eq. (4). Therefore, the yield of the saxion is estimated as

$$Y_\sigma \sim \begin{cases} 10^{-3} & \text{for } T_R \gg T_d \\ 10^{-3} \left( \frac{T_R}{T_d} \right) & \text{for } T_R \ll T_d \end{cases} . \tag{11}$$

Then, the ratio of the saxion energy density to the entropy density is given by

$$\frac{\rho_\sigma}{s} \sim \begin{cases} 10^{-3} m_\sigma & \text{for } T_R \gg T_d \\ 10^{-3} m_\sigma \left( \frac{T_R}{T_d} \right) & \text{for } T_R \ll T_d \end{cases} . \tag{12}$$

Notice that the saxion mass is comparable to the gravitino mass ($m_\sigma \sim m_{3/2}$). For $m_\sigma \simeq 10^2$ GeV the saxions dominate the energy density of the universe after the cosmic temperature $T$ cools down to $\sim 100$ MeV. However, the saxion is not stable. The relevant decay channels are $\sigma \to 2g$ and $\to 2a$, and their decay rates are estimated as

$$\Gamma_{\sigma \to 2g} = \frac{\alpha_s^2}{32\pi^3} \frac{m_\sigma^3}{F_a^2} , \tag{13}$$

$$\Gamma_{\sigma \to 2a} = \frac{C}{32\pi} \frac{m_\sigma^3}{F_a^2} , \tag{14}$$

where $C$ is the constant of $C \lesssim 1$ which depends on the model for the $U(1)_{PQ}$ symmetry breaking. If $C \simeq \mathcal{O}(1)$, the saxions decay into axions much before they dominate the universe and hence the produced axions are harmless. However, if the saxions dominate the universe when they decay, the $\sigma \to 2a$ decay channel should be suppressed enough, otherwise the extra energy density of the produced axions at the cosmic temperature $T \sim 1$ MeV spoils the success of the BBN. In order to avoid this difficulty, the branching ratio of the saxion decay into two axions should be smaller than about 0.1. Here, we simply assume that the saxion dominately decays into two gluons. When the saxions dominate the universe before they decay, the universe is reheated again by the saxion decay. The reheating temperature $T_\sigma$ is estimated as

$$T_\sigma \sim 56 \text{ MeV} \left(\frac{m_\sigma}{10^2 \text{ GeV}}\right)^{3/2} \left(\frac{10^{11} \text{ GeV}}{F_a}\right) . \tag{15}$$

Therefore, the saxion decay completes before the BBN starts. If the Peccei-Quinn breaking scale is large as $F_a \sim 10^{12}$ GeV, the saxion decay increases the entropy density of the universe by the factor $\Delta$ [10][6]

$$\Delta \sim 24 \left(\frac{10^2 \text{ GeV}}{m_\sigma}\right)^{1/2} \left(\frac{F_a}{10^{12} \text{ GeV}}\right) . \tag{16}$$

However, there is no entropy production by the saxion decay for the case of $F_a \simeq 10^{10}$–$10^{11}$ GeV. For $T_R \ll T_d$, the entropy production rate $\Delta$ is suppressed by the factor $(T_R/T_d)$ and no entropy production takes place when $T_R/T_d \lesssim 0.04$.

Furthermore, it should be noted that the saxion may be produced effectively in the form of the coherent oscillation after the inflation. We assume here that the supergravity effects induce positive mass squared for Peccei-Quinn scalar fields[7] of order of $H_I$ during the inflation ($H_I$ denotes the Hubble parameter for the inflation). Thus, it is quite natural that the Peccei-Quinn symmetry is restored during the inflation if $H_I > F_a$.[8] The Peccei-Quinn symmetry breaking occurs when the Hubble parameter becomes comparable to the scale $F_a$, and the coherent oscillation starts. Then, the ratio of the energy density of the coherent oscillation $\rho_{\rm osc}$ to entropy density for $T \ll T_R$ is estimated as

$$\begin{aligned} \frac{\rho_{\rm osc}}{s} &= \frac{1}{8}\frac{T_R F_a^2}{M_G^2} , \\ &\simeq 10^{-6} \text{ GeV} \left(\frac{T_R}{10^{10} \text{ GeV}}\right) \left(\frac{F_a}{10^{11} \text{ GeV}}\right)^2 . \end{aligned} \tag{17}$$

Comparing it with the energy density of the saxion produced by the thermal scatterings in Eq. (12), we can safely neglect the energy density of the oscillation if $T_R \lesssim 10^{15}$ GeV for $F_a \simeq 10^{11}$ GeV.

Finally, we should comment on the axion domain walls. We have assumed that the $U(1)_{PQ}$ symmetry is restored during the inflation, and hence the axion domain walls might be formed after the inflation ends. However, this can be easily evaded by adopting a hadronic axion model [12] with the domain wall number $N_{DW} = 1$ [3].

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[6]If there is an entropy production after the QCD phase transition, the upper bound on $F_a$ is raised up above $F_a \simeq 10^{12}$ GeV [11].

[7]Peccei-Quinn fields are scalar fields responsible for the Peccei-Quinn symmetry breaking.

[8]Since the $U(1)_{PQ}$ symmetry is restored during the inflation, there is no massless mode and hence no isocurvature fluctuation is generated.

In this letter we have pointed out that the cosmological gravitino problem can be solved by the SUSY axion model which is the most natural solution to the strong CP problem. In the present model, the axino is the LSP and the gravitino is the next LSP. The gravitino decays into a pair of the axino and the axion eluding the photo-dissociation constraint on the reheating temperature $T_R \lesssim 10^8$ GeV which was obtained in the minimal SUSY standard model with an unstable gravitino of $m_{3/2} \simeq 100$ GeV–1 TeV [13]. Therefore, the present model makes thermal leptogenesis scenarios [14] to work well without the cosmological gravitino problem.[9]


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[9]The primordial lepton (baryon) asymmetry is not diluted away by the saxion decay, since we have only a small entropy production as shown in Eq. (16).

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